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Optical lock-in vibration detection using photorefractive frequency domain processing

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An optical method for vibration detection and spectral analysis based on photorefractive frequency domain processing is presented. The method utilizes the photorefractive effect in selected materials (bismuth silicon oxide) for synchronous detection of the optical phase shift of an object beam scattered from a vibrating specimen surface. Four-wave mixing and lock-in detection allow measurement of both the vibration amplitude and phase. Narrow bandwidth detection can be achieved at frequencies from the photorefractive response limit to the reciprocal of the photoinduced carrier recombination time.

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Many optical techniques for vibration detection used in applications such as laser ultrasonics are based on time domain processing using homodyne or heterodyne interferometry.[1] Vibration displacement amplitudes are recorded through interference at the photodetector and subsequent signal processing. Wide bandwidth is typically employed to obtain real-time surface motion under transient conditions. Some applications, such as structural analysis, are better served by measurements in the frequency domain that record the randomly or continuously excited vibrational spectrum. A significant signal to noise ratio improvement is gained by the reduced bandwidth of the measurement compared to the time domain methods, but at the expense of additional processing and complexity. A shortcoming of optical approaches has been the sensitivity to speckle reflections from the specimen surface. This can be corrected by limiting detection to a single speckle or by use of self-beating interferometers, such as the Fabry-Perot. A potentially more powerful method is to utilize the photorefractive effect in optically nonlinear materials. This method provides an active mechanism for compensation using the spatial and temporal characteristics of photorefractivity. Several optical frequency domain measurement methods of vibration have been proposed using photorefractive two and four wave mixing in select materials.[2-4] Most provide a response that is a nonlinear function of the specimen vibration displacement amplitude and do not provide a measure of the vibration phase. We present an extension of those earlier methods that uses an optical lock-in approach for vibration detection and spectral analysis that directly measures vibration amplitude and phase with a response proportional to the Bessel function of order one and is, therefore, linear for small amplitudes. The method accommodates rough surfaces and utilizes frequency-dependent photorefractive processing in conjunction with a single, fixed frequency narrow bandwidth detection system.

The experimental setup is shown in figure 1. A argon laser source at 514 nm, 200 mW, is split into two legs, object and reference beams. The object beam is reflected off a specimen undergoing continuous vibration. The excited vibrational modes of the specimen determine the frequency-dependent displacement amplitude of the sample surface, which is transferred into phase

modulation δ_1 of the object beam. The reference beam is frequency modulated by an electro-optic modulator at a fixed modulation depth δ_2. The modulated beams are then combined and interfere inside a bismuth silicon oxide (BSO) photorefractive crystal at an external angle between the beams of 55 degrees. A four-wave mixing configuration is used for demodulation of the photorefractive interference grating produced within the crystal. The reference beam is reflected back into the crystal along a counter-propagating path that matches the Bragg angle of the photorefractive grating in the medium. The resulting scattered wave or conjugate signal beam is then sampled at the plate beamsplitter and deflected toward the photodetector.

Several different operating modes of this configuration are possible; however, the two most useful are what we call the Power Spectrum Mode and the Swept Network Mode in analogy with common electrical frequency analysis measurements. In the above configurations, the photorefractive crystal acts as a mixing and low pass filtering element providing the benefits of lock-in detection.[5] The measured signal intensity can be calculated from the time-dependent photorefractive 1st order response theory in the single grating approximation.[6] The result, retaining only the most dominant terms, is described by the following equation[7]

$$I(t) \sim J_0(\delta_1) J_1(\delta_1) J_0(\delta_2) J_1(\delta_2) \frac{\cos\left(\Omega t + \Psi - (\varphi_1 - \varphi_2)\right)}{\sqrt{1 + \Omega^2 \tau^2}} \qquad (1)$$

where τ is the photorefractive time constant, $\Omega = \omega_2 - \omega_1$, $\Omega\tau = \tan(\Psi)$ and $(\varphi_1 - \varphi_2)$ is the relative phase difference between the vibrating specimen surface and the electro-optic modulator.

In the Power Spectrum Mode, a random excitation is applied to the specimen while the electro-optic modulator is driven with a fixed modulation depth at the measurement frequency. The reference frequency, ω_2, is then scanned across the range of interest while monitoring the rms response at the detector. When the reference frequency approaches a vibrating mode of the specimen at a given characteristic frequency, ω_1, the response increases resulting in the power

spectrum of the vibration. The result is phase sensitive demanding that the path lengths be constant for all optical beams and that there are no other phase noise sources present. This requirement severely limits the usefulness of this approach; however, a path stabilization scheme could be implemented, as is commonly done in homodyne interferometers used for this purpose, or a quadrature dual detection scheme used.[1] An example of the Power Spectrum Mode is shown in figure 2. Here the specimen is a reflecting surface (mirror) driven externally at a fixed frequency, ω_1 ; when ω_2 is near ω_1 the response is a direct measure of the bandwidth of the photorefractive crystal. Figure 2 shows the measurement results along with the solid curve from equation (1) utilizing a response time of 0.015 s for the BSO photorefractive crystal found at the particular mixing intensities, grating spacing, etc. The measured intensity is proportional to the vibration displacement (ξ) for small amplitudes, $\delta_1 = 4\pi\xi/\lambda << 1.1$, from equation (1). Two closely spaced vibrational modes are not resolved beyond the intrinsic bandwidth of the photorefractive crystal.

The strong dependence of the results on the path dependent phase shift ($\varphi_1 - \varphi_2$) can be reduced by shifting the measurement to a fixed offset frequency ($\Omega < 1/\tau$). In this Swept Network Mode, the signal excitation and reference modulation are maintained coherent at a fixed frequency difference, $\Omega/2\pi = 25$ Hz. This operational mode insures that an AC or beat component of the conjugate signal intensity at 25 Hz is always present at the photodetector and its intensity is given by equation (1). The output is demodulated by a conventional lock-in amplifier yielding a measurement bandwidth that can be set less than the photorefractive crystal bandwidth. In this manner, both the vibration amplitude and phase are directly measured by the light intensity at the photodiode. This method discriminates against static or time varying phase shifts outside the lock-in bandwidth and can be extended to vibration frequencies from the reciprocal of the photorefractive response time (67 Hz) to the reciprocal of the recombination time of the photorefractive crystal.

The amplitude and phase spectrum of a vibrating mirror specimen with the noise level are shown in figure 3, obtained with a net demodulated power on the detector of 5 μW and a bandwidth of 1 Hz. The fundamental mechanical resonance at 18.6 kHz is clearly shown along with a weakly excited higher vibration mode around 26 kHz. Phase differences between that mode and the background motion from other modes result in the spectral shape seen near 26 kHz. Figure 3 also shows the optical system noise level that results in a minimum displacement sensitivity of approximately 0.02 Ångströms. The configuration of figure 1 allowed calibration of the displacement amplitude by comparison with the known characteristics of the electro-optic modulator utilizing homodyne intereferometry. Figure 4 shows the effect of the magnitude of the electro-optic modulator phase shift on the output response, the solid line is the expected response from equation (1).

The minimum detectable displacement obtained is some what higher than that to be expected from other optical methods, considering the very narrow bandwidth used. The reason for this is the appearance of additional terms in the demodulated intensity not accounted for in equation (1) and path length or other phase noise contributions recorded within the lock-in bandwidth. However, this photorefractive lock-in approach offers simplicity in design, alignment and operation, only the total demodulated intensity need be recorded as all interference occurs inside the photorefractive crystal. In addition, the photorefractive effect is capable of accounting for speckle reflection from rough surfaces through spatial adaptation. This was directly measured by roughening the surface of the vibrating mirror specimen used previously so that a diffuse reflection was obtained. Results consistent with those presented were obtained if the reduced intensity was taken into account.

In conclusion, a new optical technique for vibration detection based on photorefractive frequency domain processing has been presented. The method uses an optical synchronous or lock-in detection and also includes electrical lock-in detection. Sub-Ångström level detectability

has been demonstrated with fixed narrow bandwidth. The method is capable of flat frequency response over a large range, from the cutoff of the photorefractive effect to the high megahertz region and is applicable to rough surfaces. In addition, the photorefractive lock-in vibration detection method can be configured for high sensitivity, linear vibration imaging. Work on this full-field view approach is in progress.

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Figure Captions

FIG. 1 - Experimental setup for optical frequency domain processing using photorefractive four-wave mixing. PRC: photorefractive crystal; EOM: electro-optic modulator; BS: beamsplitter; E_1 and E_2: frequency modulated object and reference beams, respectively.

FIG. 2 - Power Spectrum Mode: Measurement of a surface vibrating at a fixed frequency while the reference frequency is swept.

FIG. 3 - Swept Network Mode: The amplitude spectrum (top) of a vibrating specimen (solid line) along with the noise level (dotted line) and corresponding phase shift (bottom).

FIG. 4 - Swept Network Mode: The effect of reference electro-optic modulator amplitude, δ_2, on the wave mixing process. Solid line is equation (1). Specimen displacement was fixed at ξ_1 = .15 nm rms.

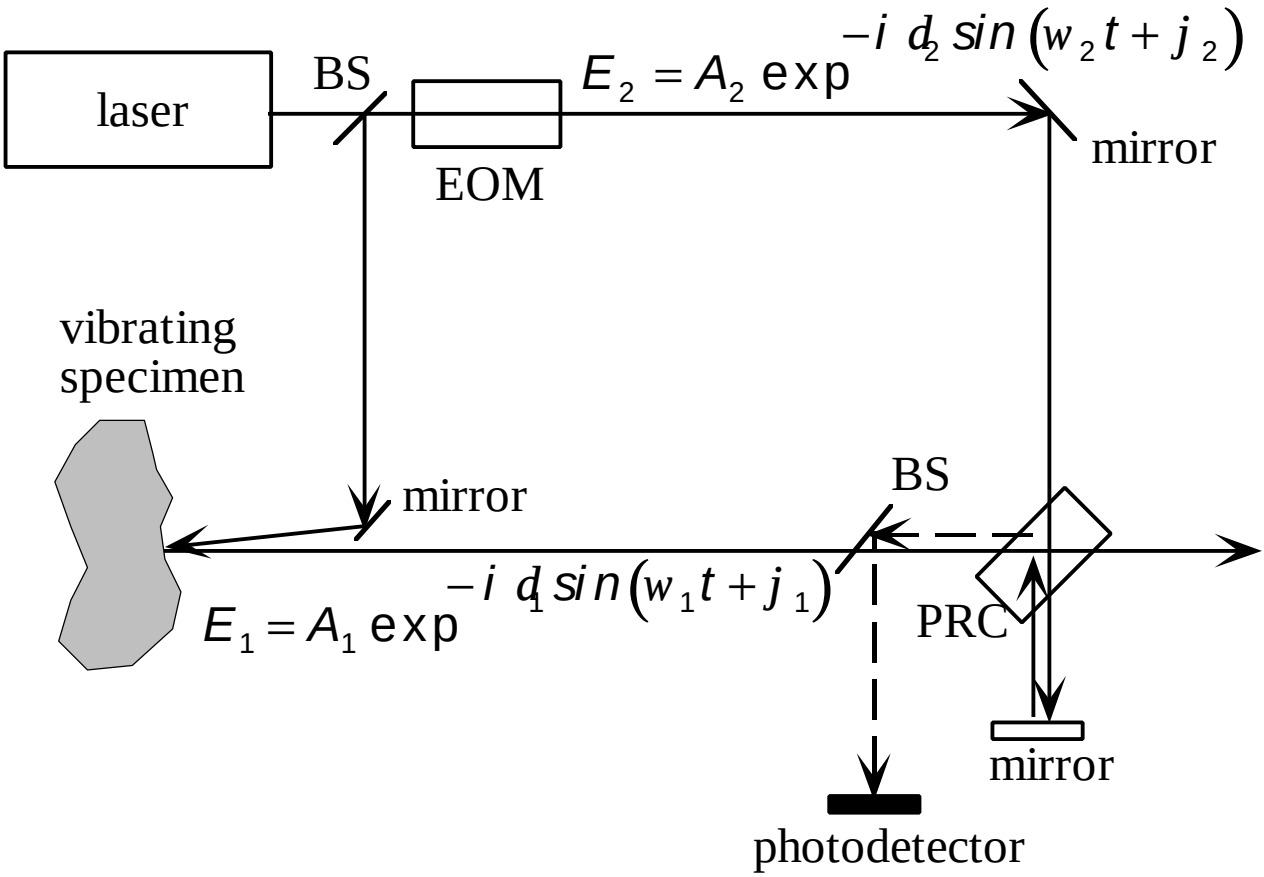
laser
BS
EOM
$E_2 = A_2 \exp^{-i\ d_2 \sin(w_2 t + j_2)}$
mirror
vibrating
specimen
mirror
BS
$E_1 = A_1 \exp^{-i\ d_1 \sin(w_1 t + j_1)}$
PRC
mirror
photodetector

FIG. 1 - Thomas Chatters Hale, *Applied Physics Letters*.

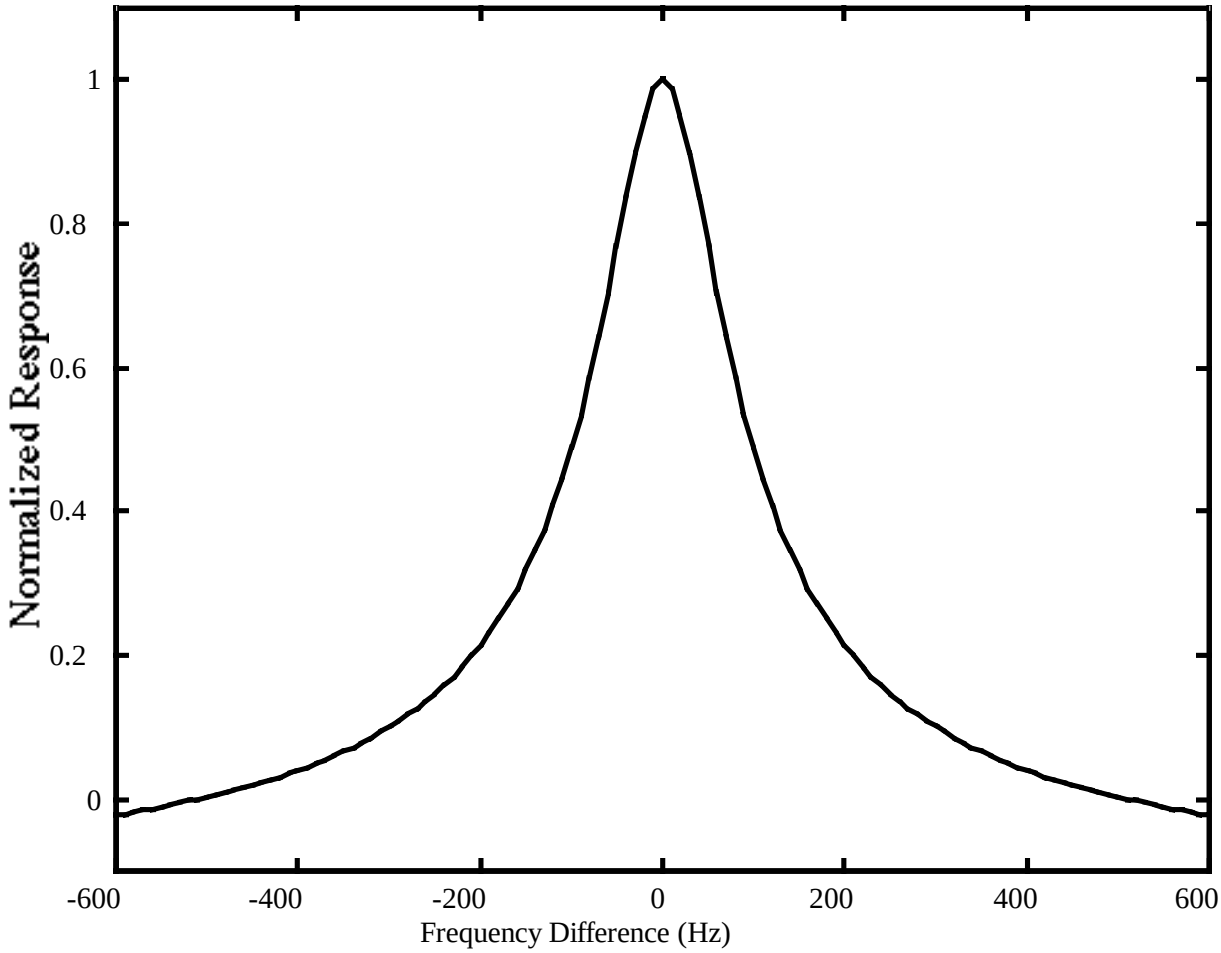

FIG. 2 - Thomas Chatters Hale, *Applied Physics Letters.*

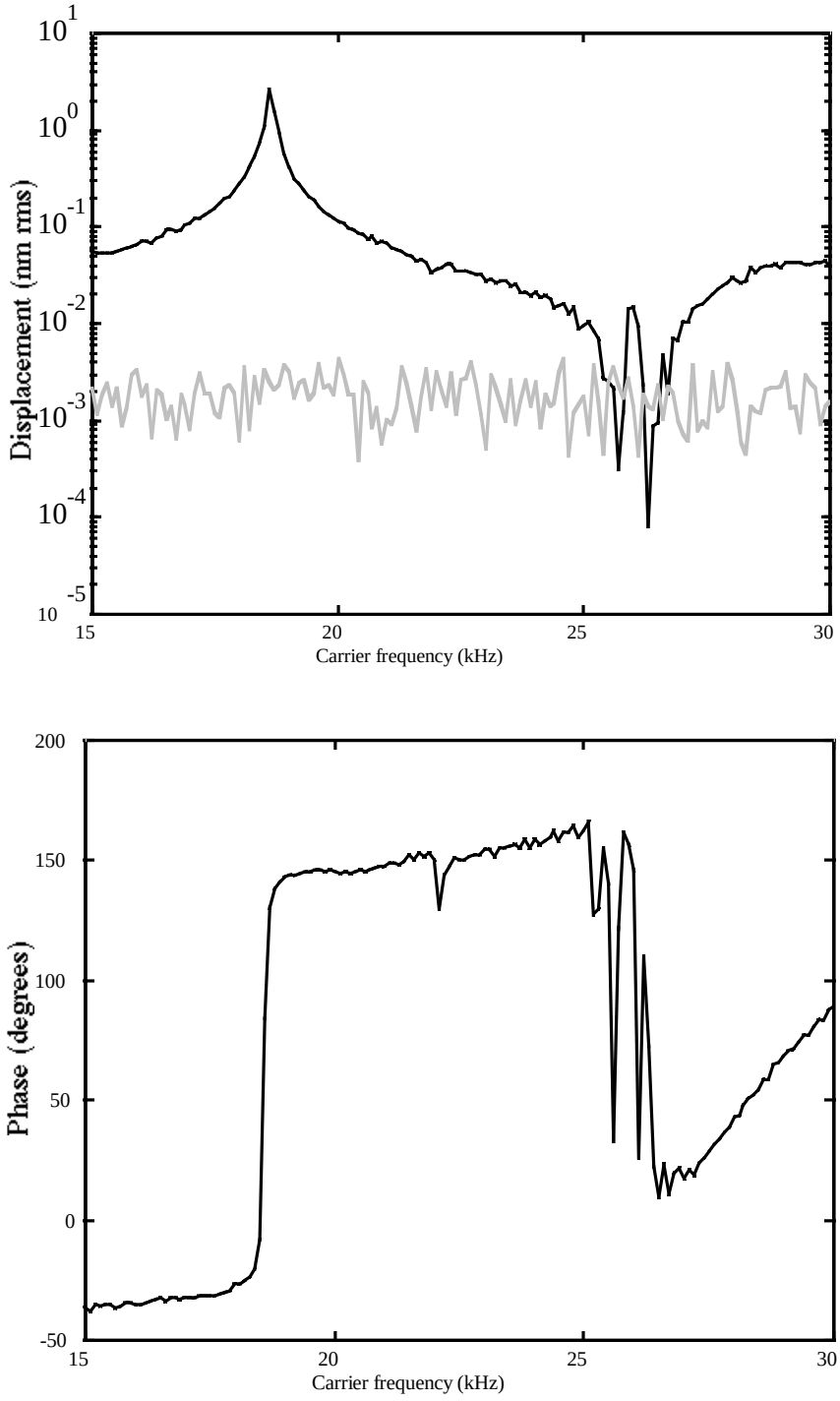

FIG. 3 - Thomas Chatters Hale, *Applied Physics Letters.*

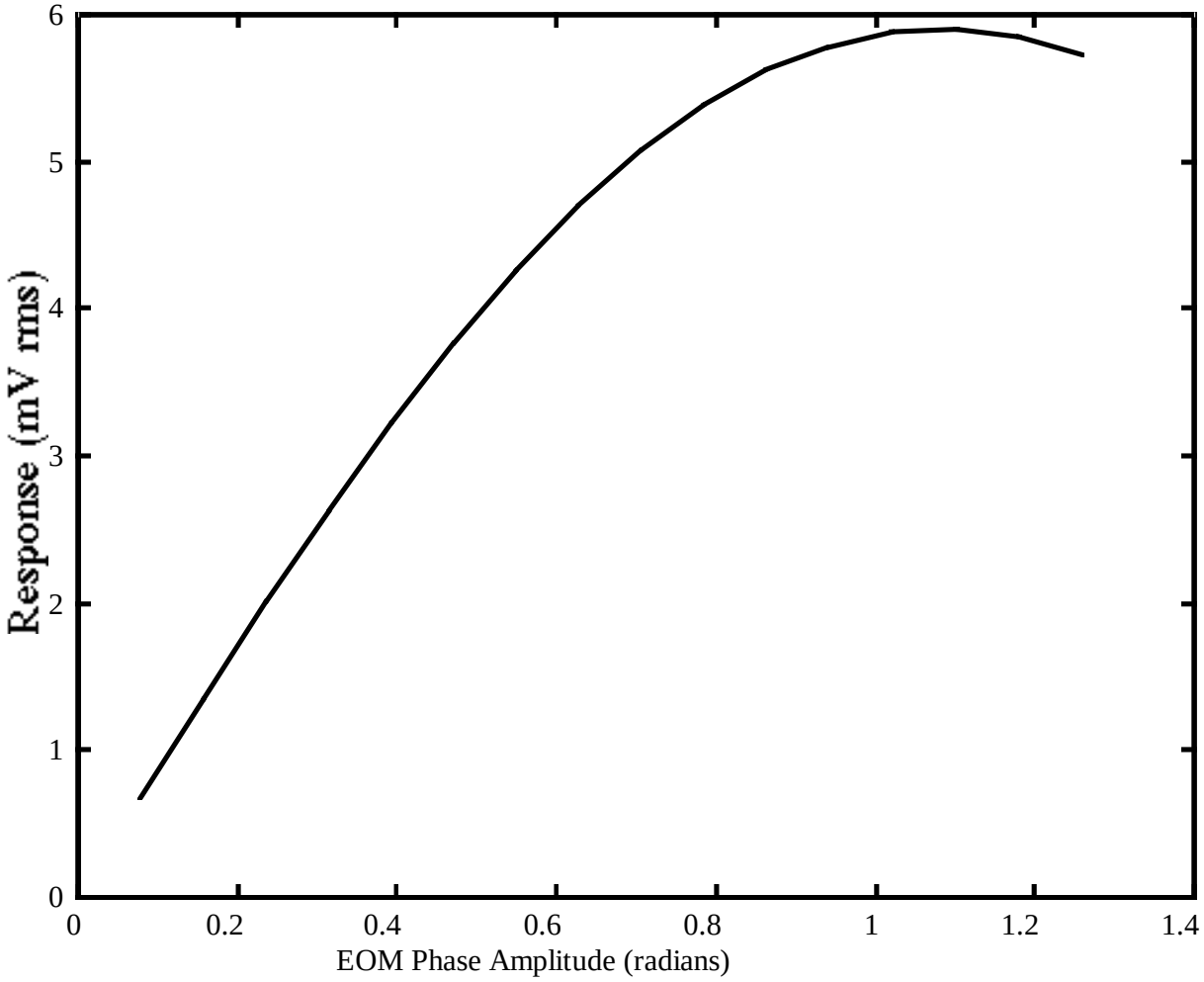

FIG. 4 - Thomas Chatters Hale, *Applied Physics Letters.*